A PRELIMINARY INVESTIGATION OF THE USE OF LIFT CONTROL IN MANEUVERING FLIGHT

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ABSTRACT

A very preliminary investigation was conducted in which a variable stability/variable lift Navion aircraft was flown through limited maneuvers by a Navy fighter pilot. The flying qualities of a given configuration were compared using the three methods of control available; elevator, direct lift control (DLC), and a combination of lift control and elevator. The configurations simulated were a high and low value of the force derivative L_α / V_0 at known values of good and bad short period dynamics. The results are presented in the form of very tentative iso-opinion maps of the two parameters, elevator and flap control sensitivities.

Both DLC and combination control improved the flying qualities at a low value of the parameter $\left.\frac{n_z}{\alpha}\right]_{ss}$ and good short period dynamics.

Combination control did not improve the flying qualities at low $\left.\frac{n_z}{\alpha}\right]_{ss}$ and a low short period frequency <u>and</u> damping ratio. Further flight tests are required to substantiate this result.

DLC was not a satisfactory method of control at a low short period frequency <u>and</u> damping ratio.

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b	wingspan (ft)
$\bar{c}$	mean aerodynamic chord (ft)
C_D	nondimensional drag coefficient
C_L	nondimensional lift coefficient
D_α	dimensional drag due to $\Delta\alpha$ (ft/ sec^2)($\equiv \frac{1}{m}\frac{\partial D}{\partial \alpha}$)
DLC	Direct Lift Control
D_V	dimensional drag due to ΔV (sec^{-1})($\equiv \frac{1}{m}\frac{\partial D}{\partial V}$)
E	elevator configuration
F	flap configuration
g	gravitational acceleration (ft/ sec^2)
I_y	pitching moment of inertia (slug-ft^2)
k_y	radius of gyration (ft)
K	flap to elevator gearing ratio ($\equiv \frac{\delta_f^{\,o}}{\delta_s \text{in.}} / \frac{\delta_f^{\,o}}{\delta_s \text{in.}}$)
K	combination configuration
$\frac{L_\alpha}{V_o}$	dimensional lift due to $\Delta\alpha$ (sec^{-1})($\equiv \frac{1}{mV_o}\frac{\partial L}{\partial \alpha}$)
$\frac{L_{\delta_e}}{V_o}$	dimensional lift due to δ_e (sec^{-1})($\equiv \frac{1}{mV_o}\frac{\partial L}{\partial \delta_e}$)
$\frac{L_{\delta_f}}{V_o}$	dimensional lift due to δ_f (sec^{-1})($\equiv \frac{1}{mV_o}\frac{\partial L}{\partial \delta_f}$)
$\frac{L_V}{V_o}$	dimensional lift due to ΔV(ft^{-1})($\equiv \frac{1}{mV_o}\frac{\partial L}{\partial V}$)
$\frac{L_{\delta_s}}{V_o}$	dimensional lift due to δ_s(sec^{-1})($\equiv \frac{1}{mV_o}\frac{\partial L}{\partial \delta_s}$)

m	airplane mass (slugs)
M_α	dimensional pitching moment due to $\Delta\alpha$ (sec^{-2})($\equiv \frac{1}{I_y} \frac{\partial M}{\partial \alpha}$)
$M_{\dot\alpha}$	dimensional pitching moment due to $\dot\alpha$ (sec^{-1})($\equiv \frac{1}{I_y} \frac{\partial M}{\partial \dot\alpha}$)
M_{δ_e}	dimensional pitching moment due to δ_e (sec^{-2})($\equiv \frac{1}{I_y} \frac{\partial M}{\partial \delta_e}$)
M_{δ_f}	dimensional pitching moment due to δ_f (sec^{-2})($\equiv \frac{1}{I_y} \frac{\partial M}{\partial \delta_f}$)
M_{δ_s}	dimensional pitching moment due to δ_s(in.-sec^{-2})($\equiv \frac{1}{I_y} \frac{\partial M}{\partial \delta_s}$)
$M_{\dot\theta}$	dimensional pitching moment due to $\dot\theta$ (sec^{-1})($\equiv \frac{1}{I_y} \frac{\partial M}{\partial \dot\theta}$)
M_V	dimensional pitching moment due to ΔV (ft^{-1}-sec^{-1})($\equiv \frac{1}{I_y} \frac{\partial M}{\partial V}$)
n_z	normal acceleration (Δg)
PVSN	Princeton variable-stability Navion
q	dynamic pressure (lb/ft^2)
S	wing area (ft^2)
s	Laplace operator
ss	steady state
T_V	dimensional thrust due to V(sec^{-1})($\equiv \frac{1}{m} \frac{\partial T}{\partial V}$)
V	airspeed (ft/sec)
V_o	trim airspeed (ft/sec)
W	airplane gross weight (lb)
α	angle of attack (radians)
δ_e	elevator deflection (radians)
δ_f	flap deflection (radians)
δ_s	stick deflection (in.)
θ	pitch attitude (radians)

$\frac{\delta_e}{\delta_s}$	elevator to stick gearing ratio (radians/ inch)
$\frac{\delta_f}{\delta_s}$	flap to stick gearing ratio (radians/ inch)
ω_{ph}	phugoid frequency (rad/ sec)
ω_{sp}	short period frequency (rad/ sec)
ζ_{ph}	phugoid damping ratio
ζ_{sp}	short period damping ratio
$(\dot{\ })$	time rate of change ($\frac{\partial}{\partial t}$)

INTRODUCTION

Studies sponsored by the U.S. Navy (References 1 and 2) have found that Direct Lift Control (DLC) is an effective means of controlling the flight path of an airplane making a carrier approach. DLC controls the longitudinal response of an airplane by a direct increase in lift at a constant angle of attack and airspeed. The possibility exists that DLC could be used to advantage in some flight regime other than the landing approach.

This investigation had two objectives:

1) To determine if the Princeton Variable Stability/ Variable Lift Navion (PVSN) was suitable for an investigation of the use of DLC for maneuvering flight.
2) To gain an understanding of some of the longitudinal dynamic response parameters most likely to influence the selection of lift control as a primary or supplemental controller for maneuvering flight.

It was immediately obvious that an attempt to use the PVSN to simulate a high performance aircraft in maneuvering flight would require quite an extension of the capabilities of the PVSN. Nevertheless, it was hoped that some worthwhile results would develop from the limited capabilities.

For this investigation the flying qualities of a given aircraft configuration were evaluated using the three methods of control available; elevator, direct lift control, and a combination of lift control and elevator.

Priority commitments on the PVSN, development problems, and unusually severe spring weather limited the scope of the investigation to a very preliminary study.

THEORY

1. Equations of Motion

The small perturbation three degree of freedom equations of motion following the notation of Reference 3 are:

$$
1.)\quad \begin{bmatrix} s+(D_v-T_v) & D_\alpha - g & g \\ \dfrac{L_v}{V_o} & s+\dfrac{L_\alpha}{V_o} & -s \\ -M_v & -(M_{\dot\alpha}s+M_\alpha) & (s-M_{\dot\theta})s \end{bmatrix} \begin{bmatrix} \Delta V \\ \Delta\alpha \\ \Delta\theta \end{bmatrix} = \begin{bmatrix} 0 \\ -\dfrac{L_{\delta_s}}{V_o} \\ M_{\delta_s} \end{bmatrix} \delta_s
$$

The forcing functions on the right side represent the summation of the forces due to elevator and flap deflections responding to a stick input. The drag terms and lift due to elevator have been neglected for the analysis.

2. Direct Lift Control

The flight path of an airplane is normally changed by rotating the airplane to a new angle of attack and lift coefficient with the elevator. DLC essentially changes the lift coefficient at a constant angle of attack and airspeed through flap deflection. Figure 1 (from Reference 4) represents the PVSN lift coefficient versus angle of attack for various flap deflections.

Reference 1 found that DLC provided a more rapid means of changing the flight path by eliminating the time lag associated with rotating the airplane when using normal longitudinal control. In effect, the normal acceleration produced by DLC integrated into an actual altitude change more rapidly. This rapid response gave better glide path control on carrier approaches. It was not known if this more rapid acceleration response would be of benefit in maneuvering flight.

It should be noted that the F-8 aircraft used in the study of Reference 1 had the lift devices, drooped ailerons, controlled by means of a separate thumb wheel controller mounted on the control stick. For this investigation the lift devices, flaps, were connected directly to the normal control stick.

3. Test Program Variables

The factors that affect the longitudinal handling qualities of an aircraft have been the subject of many investigations. Perhaps the most important of these factors are: Short period dynamics, $\frac{L_\alpha}{V_o}$, stick sensitivity, stick force/ g, turbulence, and true airspeed. The incorporation of the flaps as a supplemental controller adds at least one more factor, flap to elevator gearing ratio $\left(K = \frac{\delta_f^{\,o}}{\delta_s \text{in.}} \Big/ \frac{\delta_e^{\,o}}{\delta_s \text{in.}}\right)$.

The parameters selected for study in this investigation were flap to elevator gearing ratio and $\frac{L_\alpha}{V_o}$. Because short period dynamics are so important to the handling qualities of an airplane, it was decided to duplicate the evaluations at known good and bad values of short period dynamics. The actual tested configurations are listed in Table I.

Figure 2 presents responses of the PVSN to elevator and flap step inputs at a high and low value of $\frac{L_\alpha}{V_o}$. The elevator input produces almost the same angle of attack change in the two cases, but the resulting acceleration and attitude responses are much smaller for the low $\frac{L_\alpha}{V_o}$. The responses to the flap step inputs are essentially the same for the two values of $\frac{L_\alpha}{V_o}$. Only minor differences are noted. Ideally, if $\frac{L_\alpha}{V_o} = \frac{L_{\delta_e}}{V_o} = 0$, an elevator input only succeeds in changing the angle of attack, generating no acceleration to maneuver the aircraft. This suggests that lift control might be most beneficial at low values of $\frac{L_\alpha}{V_o}$.

If constant speed is assumed and the drag equation is neglected, the following approximate aircraft short period transfer functions can be derived from Equation 1.

$$2.)\quad \frac{\dot{\theta}(s)}{\delta_s(s)} = \frac{\left(M_{\delta_s} - \frac{L_{\delta_s}}{V_o} M_{\dot{\alpha}}\right)s + \left(M_{\delta_s}\frac{L_\alpha}{V_o} - M_\alpha \frac{L_{\delta_s}}{V_o}\right)}{s^2 + 2\zeta_{sp}\,\omega_{sp}\,s + \omega_{sp}^2}$$

$$3.)\quad \frac{\alpha(s)}{\delta_s(s)} = \frac{-\frac{L_{\delta_s}}{V_o}\,s + \left(M_{\delta_s} + M_{\dot{\theta}}\frac{L_{\delta_s}}{V_o}\right)}{s^2 + 2\zeta_{sp}\,\omega_{sp}\,s + \omega_{sp}^2}$$

$$4.)\quad \frac{n_z(s)}{\delta_s(s)} = \frac{V}{g}\,\frac{\frac{L_{\delta_s}}{V_o}\,s^2 + \left(-\frac{L_{\delta_s}}{V_o} M_{\dot{\theta}} - \frac{L_{\delta_s}}{V_o} M_{\dot{\alpha}}\right)s + \left(M_{\delta_s}\frac{L_\alpha}{V_o} - M_\alpha \frac{L_{\delta_s}}{V_o}\right)}{s^2 + 2\zeta_{sp}\,\omega_{sp}\,s + \omega_{sp}^2}$$

The denominator is the characteristic equation of the system.

$$5.)\quad s^2 + 2\zeta_{sp}\,\omega_{sp}\,s + \omega_{sp}^2 = s^2 + \left(\frac{L_\alpha}{V_o} - M_{\dot{\theta}} - M_{\dot{\alpha}}\right)s + \left(-M_\alpha - M_{\dot{\theta}}\frac{L_\alpha}{V_o}\right)$$

Applying the final value theorm to these second order systems yields expressions for the steady state $\dot{\theta}$, α, and n_z per unit stick input.

$$6.)\quad \left.\frac{\dot{\theta}}{\delta_s}\right]_{ss} = \frac{M_{\delta_s}\frac{L_\alpha}{V_o} - M_\alpha \frac{L_{\delta_s}}{V_o}}{\omega_{sp}^2} \quad \text{radian/ second/ inch}$$

$$7.)\quad \left.\frac{\alpha}{\delta_s}\right]_{ss} = \frac{M_{\delta_s} + M_{\dot{\theta}}\frac{L_{\delta_s}}{V_o}}{\omega_{sp}^2} \quad \text{radian/ inch}$$

$$8.)\quad \left.\frac{n_z}{\delta_s}\right]_{ss} = \frac{V}{g}\;\frac{M_{\delta_s}\dfrac{L_\alpha}{V_o} - M_\alpha \dfrac{L_{\delta_s}}{V_o}}{\omega_{sp}^2} \qquad \Delta g/\text{ inch}$$

The relative amplitude and phase of the various responses to stick inputs can be obtained by taking the ratio of the particular transfer functions.

$$\frac{n_z(s)}{a(s)} = \frac{n_z(s)/\delta_s(s)}{\alpha(s)/\delta_s(s)}$$

$$9.)\quad = \frac{V}{g}\;\frac{\dfrac{L_{\delta_s}}{V_o}\, s^2 + \left(-\dfrac{L_{\delta_s}}{V_o} M_{\dot{\theta}} - \dfrac{L_{\delta_s}}{V_o} M_{\dot{\alpha}}\right)s + \left(M_{\delta_s}\dfrac{L_\alpha}{V_o} - M_\alpha \dfrac{L_{\delta_s}}{V_o}\right)}{-\dfrac{L_{\delta_s}}{V_o}\, s + \left(M_{\delta_s} + M_{\dot{\theta}}\dfrac{L_{\delta_s}}{V_o}\right)}$$

The steady state relation is:

$$10.)\quad \left.\frac{n_z}{\alpha}\right]_{ss} = \frac{V}{g}\;\frac{M_{\delta_s}\dfrac{L_\alpha}{V_o} - M_\alpha \dfrac{L_{\delta_s}}{V_o}}{M_{\delta_s} + M_{\dot{\theta}}\dfrac{L_{\delta_s}}{V_o}} \qquad \Delta g/\text{ radian}$$

Substitution of $K = \dfrac{\delta_f^{\,o}}{\delta_s \text{ in.}} \Big/ \dfrac{\delta_e^{\,o}}{\delta_s \text{ in.}}$ into equations 7, 8 , and 10 yields:

$$11.)\quad \left.\frac{\alpha}{\delta_s}\right]_{ss} = \frac{\delta_e}{\delta_s}\;\frac{M_{\delta_e} + M_{\dot{\theta}}\dfrac{L_{\delta_f}}{V_o}K}{\omega_{sp}^2} \qquad \text{radians/ inch}$$

$$12.)\quad \left.\frac{n_z}{\delta_s}\right]_{ss} = \frac{V}{g}\;\frac{\delta_e}{\delta_s}\;\frac{M_{\delta_e}\dfrac{L_\alpha}{V_o} - M_\alpha \dfrac{L_{\delta_s}}{V_o}K}{\omega_{sp}^2} \qquad \Delta g/\text{ inch}$$

$$13.)\quad \left.\frac{n_z}{\alpha}\right]_{ss} = \frac{V}{g}\,\frac{M_{\delta_e}\dfrac{L_\alpha}{V_o} - M_\alpha \dfrac{L_{\delta_f}}{V_o}\,K}{M_{\delta_e} + M_{\dot{\alpha}}\dfrac{L_{\delta_f}}{V_o}\,K}\ \Delta g/\text{radians}$$

Equations 11 and 12 represent the approximate system gains available to the pilot for controlling α and n_z for a given stick to elevator gearing ratio and K. For elevator control, equation 13 reduces to

$$\left.\frac{n_z}{\alpha}\right]_{ss} = \frac{V}{g}\,\frac{L_\alpha}{V_o}$$

This parameter is proportional to wing loading and slope of the lift curve at constant dynamic pressure. The addition of lift control now permits variation of this parameter with K.

Figure 4 presents the responses of the PVSN ($L_\alpha = .75$) to a unit stick step input for three values of K. The primary effect of increasing K is the generation of more acceleration per unit angle of attack change.

Initially, it was hoped to study the effects of varying K on the flying qualities for each selected configuration. Time did not permit this and the pilot selected one preferred K for each configuration.

Two control surfaces are controlled through one stick controller; therefore, only two of the three variables M_{δ_s}, $\frac{L_{\delta_s}}{V_o}$, and K are linearly independent. Selection of a given M_{δ_s} and K determine a unique $\frac{L_{\delta_s}}{V_o}$. Conversely for a given M_{δ_s} and $\frac{L_{\delta_s}}{V_o}$, K is uniquely determined.

EXPERIMENTAL PROCEDURE

1. Description of Airplane

The North American Navion used in this investigation is shown in Figure 4. The physical characteristics and aerodynamic parameters of the Navion are listed in Table II.

Longitudinal and lateral dynamic characteristics can be varied through various feedbacks to a modified electric 3 axis autopilot. Electric servos position the control surfaces in proportion to angular rates, angle of attack, and sideslip angle.

The right side controls and cockpit instruments have been modified to resemble those of a jet fighter as shown in Figure 5. The conventional yoke has been replaced with a floor mounted stick controller. The longitudinal stick force gradient of 3 lb/in is provided by a simple spring arrangement with negligible threshold forces.

Prior to this investigation the flap system was modified to permit its use as a second longitudinal controller. The hydraulic flap actuator was connected to an electric control servo for positioning.

Two variable gain potentiometers translate longitudinal stick motion into electrical signals which are fed to the flap and elevator control servos. Control sensitivity M_{δ_s} (stick to elevator gearing) and $\frac{L_{\delta_s}}{V_o}$ (stick to flap gearing) can be varied independently with these variable gain potentiometers.

The flaps are normally positioned 10° down when used as control surfaces. Flap deflection is limited to 0-25° down for structural consideration.

Provision is also incorporated to control the flaps through a spring-loaded stick-mounted thumb wheel or through a spring loaded toggle switch on top of the stick. A selector switch permits the option of proportional position or proportional rate control for the thumb wheel controller. Bang-bang position or bang-bang rate can be selected for the toggle switch.

This same variable flap system permits the somewhat unique variation of the force derivative, $\frac{L_\alpha}{V_o}$, through feedback of the angle of attack to the flap servo. Effectively, the slope of the lift curve is changed through flap actuation in response to angle of attack changes.

Down flap produces a nose down pitching moment on the aircraft which opposes the desired normal acceleration increase of the flap deflection. It was necessary to install a flap to elevator interconnect to cancel out this flap pitching moment permitting true "lift control." A position potentiometer was connected to the flap. This potentiometer converts flap position to an electrical signal which is fed through a variable gain potentiometer to the elevator servo. The servo produces an elevator pitching moment that cancels the moment due to flap deflection.

Suitable safety devices were built into the autopilot system. Each servo was equipped with a clutch that permitted manual overriding of the electric auotpilot by the safety pilot. The safety pilot rode in the left seat and had the normal Navion control system. The system had a disengage button on each control stick. It would automatically disengage if 12° up or downpitch or 45° bank angles were exceeded, or if a "hand over" signal was received. A more complete description of the basic autopilot can be found in References 5 and 6.

2. Analog Matching

The basic Navion longitudinal derivatives were adjusted from those found in Reference 5 at 105 knots to the test speed of 95 knots. The complete three degrees of freedom equation of motion were set up on a Pace TR-48 analog computer. Stick, elevator, and flap positions, pitch rate and acceleration were telemetered from the aircraft in flight to a ground station near the analog computer. After proper scaling the elevator and flap positions were used as forcing functions into the analog model on the computer. Computer responses of $\dot{\theta}$ and n_z were compared to the actual

aircraft $\dot{\theta}$ and n_z responses on a four channel Sandborn recorder. The derivatives had to be adjusted slightly from the computed values to account for power effects and the 10° down flap trim position. The matched derivatives are listed in Table II.

The computer M_{δ_f} was then set to zero and the flap to elevator interconnect gain setting in the aircraft was varied until the actual aircraft moment due to flap deflection was cancelled and the responses to flap inputs matched.

The desired aircraft short period dynamics were obtained by varying M_{α} and $M_{\dot{\theta}}$ for each $\frac{L_{\alpha}}{V_o}$. These computed derivatives were set on the computer and the aircraft gain settings were varied until the responses to stick inputs matched. The computer operator was in radio contact with the airplane for the gain adjustments.

3. <u>Phugoid Mode</u>

The conventional short period approximation is:

$$s^2 + 2\zeta_{sp}\,\omega_{sp}\,s + \omega_{sp}^{\;2} = s^2 + \left(\frac{L_{\alpha}}{V_o} - M_{\dot{\theta}} - M_{\dot{\alpha}}\right)s - \left(\frac{L_{\alpha}}{V_o} M_{\dot{\theta}} + M_{\alpha}\right)$$

Because the basic Navion short period frequency and damping ratio were so good, high destabilizing gains on M_{α} and $M_{\dot{\theta}}$ were required to simulate the very low frequency and damping ratio configurations. Aerodynamically unrealistic <u>positive</u> values of $M_{\dot{\theta}}$ were required. This resulted in a relatively high frequency unstable phugoid mode for the high $\frac{L_{\alpha}}{V_o}$ configuration and an almost neutral low frequency phugoid mode for the low $\frac{L_{\alpha}}{V_o}$ case. The computed values of M_{α} and $M_{\dot{\theta}}$ and the phugoid dynamics are listed in Table I. These phugoid characteristics were not noticed by the evaluation pilot in the relatively close control of the maneuvering task and did not detract from the evaluations.

4. Selection of Controller

Initially it was not known which of the three flap controllers (stick, thumb wheel, or trim button) available to the pilot would be used. During the first trial flight the evaluation pilot found it difficult to perform a smooth coordinated maneuver requiring both lateral and longitudinal inputs using the thumb or trim button controller for the flaps. The normal stick controller was a more natural method of control and was used thereafter.

5. Evaluation Task

Early in the program it was determined that the PVSN maneuvering capability using DLC was very limited for structural and aerodynamic reasons. The maneuvers were performed above 7000 feet to escape turbulence. Very little excess power was available. The most practical speed was 95 knots. At this speed full flap deflection produced a maximum of .3g's. The maneuvers were performed at almost constant speed for two reasons:

1. The matched derivatives were only valid for small perturbations from the matching speed.

2. Angle of attack changes resulting from airspeed changes of $\pm$ 12 knots from the trim speed caused the flaps to hit the limit stops due to the $\frac{L_\alpha}{V_o}$ simulation.

For the final evaluation maneuver the aircraft was trimmed at 95 knots, level flight at 7000 ft. The aircraft was maneuvered through several turns and reversals. Mild climbs and dives were executed. Finally, a fixed pipper on the windshield was used to track the horizon in a simulated tracking exercise.

The lateral dynamic characteristics were held constant at representatively good values. The evaluation pilot selected preferred rudder and aileron control sensitivities before the evaluation runs.

6. Evaluation Pilot and Rating System

The author of the report was the evaluation pilot for all configurations. He is a Naval Aviator with over 1600 flight hours, the majority in operational fighters.

The Cooper rating scale was used by the evaluating pilot to evaluate each configuration. A copy of the Cooper rating scale is listed in Table III.

7. Test Sequence

One flight was spent by the evaluation pilot selecting the optimum stick sensitivities for the test configurations.

The actual evaluation runs were made in a set sequence. First the normal elevator configuration was evaluated to provide a standard of comparison, next the DLC configuration was evaluated, then the combination of elevator and lift control was evaluated. After each evaluation the pilot assigned a Cooper rating to the configuration and wrote down his comments while the safety pilot changed the configuration. Each configuration required about 10 minutes to evaluate. Some were evaluated a second and third time to confirm the exact reasons for the ratings.

RESULTS

Each of the four basic configurations (1 through 4) were evaluated using the three types of control available. These sub-configurations are designated by a suffix letter indicated the type of controller used. (E = elevator, F = flap, and K = combination). The sub-configurations are listed in Table IV.

1. Optimum Control Sensitivities

The resulting preferred elevator alone and flap alone sensitivities were a compromise between steady state stick forces in turns and pull ups, transient maneuvering forces in tracking and turning flight, and primarily good attitude response. The addition of the flap as a supplemental controller permitted the somewhat independent control of acceleration and attitude response.

The preferred elevator control sensitivities, M_{δ_s} of the combination configurations were found to be the same optimum M_{δ_s} determined evaluating the configurations with elevator alone. The pilot preferred not to reduce M_{δ_s} as the flap control sensitivity, $\frac{L_{\delta_s}}{V_o}$ was increased. Acceleration produced by flap deflection would eventually integrate into an attitude change, but the pilot sensed a loss of correlation between stick inputs and attitude response as M_{δ_s} was decreased. The pilot preferred rapid and positive control of attitude in the limited maneuvers performed. Therefore, M_{δ_s} was held constant for configurations E and K. The pilot selected a preferred $\frac{L_{\delta_s}}{V_o}$ for the combination configurations and then a preferred $\frac{L_{\delta_s}}{V_o}$ for the DLC configuration.

Reference 7 concluded that for $\left.\frac{n_z}{\alpha}\right]_{ss} < 10 \frac{g}{rad}$ pilots tended to select longitudinal control sensitivities (stick gains) based on a constant value of $\left.\frac{\alpha}{\delta}\right]_{ss}$. The actual value of $\left.\frac{\alpha}{\delta}\right]_{ss}$ was a function of the short period frequency and damping ratio.

These parameters, $\left.\frac{\alpha}{\delta}\right]_{ss}$, $\left.\frac{n_z}{\delta}\right]_{ss}$, and $\left.\frac{n_z}{\alpha}\right]_{ss}$, were calculated for each configuration using the selected elevator/ stick gearing ratios and flap/ elevator gearing ratios, and are listed in Table IV. These parameters were plotted for comparison with other data. Little correlation of the data of this investigation was found between the pure lift controller and the other two methods of control. Therefore, only the $\left.\frac{\alpha}{\delta}\right|_{ss}$ gain versus $\left.\frac{n_z}{\alpha}\right|_{ss}$ for configurations E and K are presented in Figure 6a. For normal elevator control, the parameters reduce to:

$$\left.\frac{\alpha}{\delta}\right]_{ss} = \frac{\delta_e}{\delta_s} \frac{M_{\delta_e}}{\omega_{sp}^2}$$

$$\left.\frac{n_z}{\alpha}\right]_{ss} = \frac{V}{g} \frac{L_\alpha}{V_o}$$

The incorporation of the lift force (neglected in Reference 7) displaces the combination configuration gains both vertically and horizontally from the basic elevator alone gains in Figure 6a. The low frequency short period configurations were characterized by slow responses with easily excited pitch oscillations. For these configurations Figure 6a indicates that relatively high values of $\frac{\alpha}{\delta}_{ss}$ were selected for good positive attitude control. The high frequency short period configurations were very responsive in pitch and lower values of gains were selected. These results are consistent with the results of Reference 7 though a direct comparison cannot be made because different frequencies and damping ratios were investigated.

DLC is designed to produce maneuvering accelerations at essentially constant angle of attack. The gain parameter $\left.\frac{\alpha}{\delta}\right]_{ss}$ obviously is not as significant to the selection of preferred stick gains for a pure lift controller. Some insight is provided if $\left.\frac{n_z}{\delta}\right]_{ss}$ is plotted versus the <u>magnitude</u> of $\left.\frac{n_z}{\alpha}\right]_{ss}$ as presented in Figure 6b. For pure lift control the equations reduce to:

$$\left.\frac{n_z}{\delta}\right]_{ss} = \frac{V}{g} \frac{-M_\alpha \frac{L_{\delta_f}}{V_o} \frac{\delta_f}{\delta_s}}{\omega_{sp}^2}$$

$$\left.\frac{\alpha}{\delta}\right]_{ss} = \frac{M_{\dot{\theta}} \frac{L_{\delta_f}}{V_o} \frac{\delta_f}{\delta_s}}{\omega_{sp}^2}$$

$$\left.\frac{n_z}{\alpha}\right]_{ss} = \frac{-V}{g} \frac{M_\alpha}{M_{\dot{\theta}}}$$

For flap deflection $\left.\frac{\alpha}{\delta}\right]_{ss}$ is normally negative, indicating a decrease in the angle of attack due to pitch damping. The positive $M_{\dot{\theta}}$ required for the low short period frequency and damping ratio simulation produced unrealistic small positive angle of attack changes. Therefore, the parameter $\left.\frac{n_z}{\alpha}\right]_{ss}$ can have either sign.

Essentially the same $\left.\frac{n_z}{\delta}\right]_{ss}$ gains were selected for configurations 1F and 2F as expected. This was not true of the low short period and damping configurations. No definite conclusions can be made from so little data. However, almost the same control sensitivities were selected for both configurations 3F ($\frac{L_{\delta_s}}{V_o}$ = .0435 rad/sec/in) and 4F ($\frac{L_{\delta_s}}{V_o}$ = .0495 rad/sec/in). It is believed that the

pilot selected his preferred gains for these two configurations primarily on the basis of acceleration stick sensitivity. The lower value of $\left.\frac{n_z}{\delta}\right]_{ss} = \frac{-V}{g} \frac{M_\alpha \frac{L_{\delta_s}}{V_o}}{\omega_{sp}^2}$ for configuration 4F results from the much lower angle of attack static stability (M_α = -1.9 rad/ sec^2) required to produce the same low short period frequency as that of configuration 3 (M_α = -5.0 rad/ sec^2).

The selected elevator and flap control sensitivities for each configuration are presented in Figures 7a, b, c, and d. The Cooper ratings and resulting flap to elevator gearing ratios are shown. The resulting K should be the optimum for the combination of controls, because the pilot selected both a preferred M_{δ_s} and $\frac{L_{\delta_s}}{V_o}$.

2. Exploratory Longitudinal Control Sensitivity Iso-Opinion Map

Additional evaluations (designated by K') were made at M_{δ_s} arbitrarily reduced to one-half the optimum value for configurations 2 and 4 only. The pilot selected another preferred $\frac{L_{\delta_s}}{V_o}$ for this reduced M_{δ_s}. Time did not permit more of an attempt to get a detailed gradient of the two controller sensitivities versus Cooper ratings. However, the pilot evaluated many combinations of controller sensitivities determining his preferred gains. Some very tentative iso-opinion lines are presented in Figures 7a, b, c, and d. It should be emphasized that these represent one pilot's opinion based on a very limited flight program, and should be weighed accordingly. They are presented merely as guide lines for future exploratory study.

In general, the ordinates, M_{δ_s}, and abscissas, $\frac{L_{\delta_s}}{V_o}$, of Figure 7 can be characterized by increasing stick sensitivities and lighter steady state stick forces as the gains are increased.

Excluding other considerations some preferred sensitivity can be found. Higher gains will make the aircraft too responsive to small hand motions, lower gains will require uncomfortable stick displacements.

The pilot is keenly aware of low control power $\left(\frac{L_{\delta_s}}{V_o} \cdot \delta_s\right)$ using the flap alone at low values of $\frac{L_{\delta_s}}{V_o}$. He does not have effective control of the aircraft before the stick hits the stop. This also occurs at low elevator sensitivities.

The iso-opinion maps of Figure 7 are labeled with areas of adjective comments on attitude and acceleration control and responses, steady state stick forces, and stick sensitivity. The basis for this labeling should become more apparent with the discussion of the flight test results.

Also shown in Figure 7 are radial lines of constant $\left.\frac{n_z}{\alpha}\right]_{ss}$.

$$\left.\frac{n_z}{\alpha}\right]_{ss} = \frac{V}{g} \frac{M_{\delta_e} \frac{L_\alpha}{V_o} - M_\alpha \frac{L_{\delta_f}}{V_o} K}{M_{\delta_e} + M_\alpha \frac{L_{\delta_f}}{V_o} K}$$

On the ordinate, M_{δ_s}, the lines have the magnitude $\frac{n_z}{\alpha} = \frac{V}{g} \frac{L_\alpha}{V_o}$ (K = 0). The magnitude increases clockwise as the flap to elevator gearing ratio is increased negatively (K is a negative due to differing sign conventions for flap and elevator). This parameter, $\left.\frac{n_z}{\alpha}\right]_{ss}$, indicates the pilot's ability to generate accelerations for maneuvering through angle of attack changes. A pilot correlates an attitude change with an angle of attack change in maneuvering flight. Conceptually, for constant airspeed a range of near optimum $\left.\frac{n_z}{\alpha}\right]_{ss}$ could be found for maneuvering flight. Lower values would require very large attitude (angle of attack) changes, higher values would require too little attitude change.

Pilot Evaluations

The pilot evaluation comments and ratings are listed in the Appendix. As an aid to the discussion, analog computer responses to stick step inputs for each subconfiguration scaled to the selected preferred sensitivities are presented in Figures 8a, b, and c through 11a, b, and c. Note should be taken of the increased scaling (by a factor of 2) for the low short period frequency and damping ratio configurations.

Elevator Alone Evaluations

The high $\frac{L_\alpha}{V_o}$ and high short period frequency and damping ratio configuration (1E) was rated as a "good flying aircraft" and received a Cooper rating of 2.0. Good attitude and acceleration responses were available with the elevator alone. Figure 7a indicates that this configuration has a high $\left.\frac{n_z}{\alpha}\right]_{ss} = 9.3\ \Delta g/\text{rad}$.

The low $\frac{L_\alpha}{V_o}$ high short period frequency configuration, 2E, received only a satisfactory rating of 3.5, primarily because large attitude changes were required to generate the incremental lift forces necessary to maneuver the aircraft. Figure 7b indicates a low $\left.\frac{n_z}{\alpha}\right]_{ss}$ of 3.7 $\Delta g/\text{rad}$ for this configuration.

Both low short period frequency configurations, 3E and 4E, received unacceptable ratings of 5.0 and 5.5, respectively. The configurations were very slow responding to normal stick inputs and it was necessary to overdrive to achieve rapid response. The amount of control input necessary was difficult to estimate and annoying pitch oscillations were developed easily. Configuration 4E ($\left.\frac{n_z}{\alpha}\right]_{ss}$ $= 3.7\ \Delta g/\text{rad}$) required relatively larger attitude changes than 3E ($\left.\frac{n_z}{\alpha}\right]_{ss} = 9.3$ $\Delta g/\text{rad}$).

DLC Evaluation

When flown with DLC, both low short period dynamic configurations, 3F (6.0) and 4F (6.5) were rated one Cooper rating lower than their respective basic evaluation. Figures 7c and 7d indicate improvement in $\left.\frac{n_z}{\alpha}\right]_{ss}$ for both configurations, but these improvements were made at the expense of attitude control. Both ratings suffered primarily because the easily excited pitch oscillations were difficult to damp out using a pure lift controller. The pilot needed more positive attitude control.

Both high short period frequency and damping ratio configurations, 1F and 2F, received the same satisfactory rating 3.0 when flown with DLC. Comparison of the responses of Figures 8c and 9c show very similar responses for the two configurations. Both had somewhat slow attitude response. This rating represented a decrease from the good rating of the high $\frac{L_\alpha}{V_o}$ elevator configuration, but it was an improvement over the low $\frac{L_\alpha}{V_o}$ (low $\left.\frac{n_z}{\alpha}\right]_{ss}$) elevator configuration. For the latter, the pilot commented that large attitude changes were no longer required to maneuver.

These very limited results indicate that DLC is a satisfactory method of control for limited maneuvering flight at high values of short period frequency and damping ratios, but DLC is unsatisfactory at low short period dynamics. Normal elevator control is preferred for maneuvering if the aircraft has both good attitude control and acceleration response (high $\left.\frac{n_z}{\alpha}\right]_{ss}$). At low values of $\left.\frac{n_z}{\alpha}\right]_{ss}$ and at high values of short period dynamics, a compromise between good attitude control and acceleration response is possible with DLC and flying qualities improve. This compromise is not possible at low short period frequencies and damping ratios. Good attitude response is necessary to permit the pilot to act as a pitch damper.

Combination Control Evaluations

Both high $\frac{L_\alpha}{V_o}$ combination configurations, 1K and 3K, received the same Cooper rating as their respective elevator alone evaluations. The pilot sensed the additional acceleration from the flap deflection, but good control of attitude and acceleration was obtainable with the elevator alone and no measureable improvement was noted. Configuration 3 is rated low only because of the bad short period characteristics. The combination responses of Figures 8b and 10b show minor improvements over their respective elevator alone responses. Figures 7a and 7c show only high values of $\left.\frac{n_z}{\alpha}\right]_{ss}$. Good attitude and acceleration control are obtainable over relatively large areas of control sensitivities, but both are obtainable with elevator alone. At the preferred M_{δ_s} the pilot remains indifferent to lift control until $\frac{L_{\delta_s}}{V_o}$ is increased sufficiently to cause high stick sensitivity and light steady state stick forces.

Significantly, the evaluation rating of the low $\frac{L_\alpha}{V_o}$, high short period frequency and damping ratio configuration, 2K, improved one Cooper rating to 2.5 with combination control. The pilot commented, "almost as good an aircraft as the basic Navion ($\frac{L_\alpha}{V_o}$ = 1.9)." The configuration retained good attitude control and gained good acceleration response. This improved performance is evident in the responses of Figure 9. The acceleration response is greater and the build up is much more rapid for the combination configuration. Figure 7b indicates that $\left.\frac{n_z}{\alpha}\right]_{ss}$ was increased from a low value of 3.7 to a "good value of 8.3 Δg/rad. The adjective comments on Figure 7b indicate that good attitude control and response is possible with elevator alone, but not good initial acceleration response. Good acceleration response, but not good attitude control is available with DLC alone. Only when both controllers are used in combination is a "good" rating area found for both attitude and acceleration.

Somewhat contradictory results were obtained for the other low $\frac{L_\alpha}{V_o}$ configuration, 4K. The rating did not increase but in fact decreased one-half a Cooper rating. The pilot commented "No improvement over pure elevator case." Comparison of the responses in Figure 11 show almost no improvement in the performance of the combination configuration over that of the elevator alone. Figure 7d indicates that $\left.\frac{n_z}{\alpha}\right]_{ss}$ only improved slightly to 4.25 Δg/ radian for the selected K. Relatively large attitude changes were still required to maneuver the aircraft. Therefore, the rating did not improve.

One possible reason for the decrease in rating is as follows: The configuration would not stay stabilized in angle of attack or attitude very easily. Almost continuous stick pumping was required to stabilize the aircraft in a steady turn. Large stick inputs had to be made to maneuver rapidly due to the slow response. Relative to the steady state short period value, the initial transient acceleration response shown in the combination configuration response of Figure 11b is greater than the initial transient in the other low short period combination configuration shown in Figure 10b. The pilot commented, "Flaps appear to disturb the short period a little more unless inputs are very smooth." The pilot possibly downgraded the rating due to the annoying initial transient accelerations contributed by the flaps. These could only be avoided with slow smooth inputs. They were not felt in the other low short period evaluation because they were smaller and large elevator deflections were not required to generate acceleration. Further flight testing is required to determine the exact reason for the rating.

Figure 7d gives an insight into the fundamental difficulty of this configuration. Very high flap to elevator gearing ratios are required before $\left.\frac{n_z}{\alpha}\right]_{ss}$ can be increased significantly at the optimum M_{δ_s}. Theoretically, to increase $\left.\frac{n_z}{\alpha}\right]_{ss}$ to a good value of 9.3 Δg/ rad at the optimum M_{δ_s} requires a K = -46.5. The pilot

needed positive attitude control to fly the configuration satisfactorily; therefore, no reduction in M_{δ_s} was accepted. Stick sensitivity was reasonably high with elevator alone. An ineffectual K was selected to keep stick sensitivity at a comfortable level for the combination configuration.

An adjective area of good attitude control and relatively good initial acceleration response is indicated on Figure 7d. No improvement in the Cooper rating is shown due to the very high stick sensitivities in the area. Further flight tests are needed to confirm this fact.

These very limited results indicate that for limited maneuvers the flying qualities of an aircraft with a low value of the parameter $\left.\frac{n_z}{\alpha}\right]_{ss}$ and good short period dynamics can be improved by the use of flaps in combination with the normal elevator for control. The flying qualities did not improve at a low $\left.\frac{n_z}{\alpha}\right]_{ss}$ and low short period frequency and damping ratio. This contradiction needs to be substantiated with further flight tests. The separate effects of frequency and damping ratio are not known.

Remarks

The limited results and conclusions of this investigation are based on one pilot's opinion. It was designed to be the first step into a relatively new field of investigation and succeeded in that respect. It is felt that the results are indicative of the probably results of a more extensive study, though some improvement in the results of the low short period frequency and damping ratio is highly likely with further investigation.

CONCLUSIONS AND RECOMMENDATIONS

The results of this program are qualified by the conditions under which it was flown:

a) Limited visual maneuvering flight at 7000 ft and 95 knots

b) Smooth air

c) Direct lift controlled through normal longitudinal control stick

d) One pilot's evaluation

In view of these qualifications the following conclusions are drawn:

1) The Princeton Variable-Stability Navion is suitable for an investigation of the use of DLC in very limited maneuvers only.

2) DLC is a satisfactory method of longitudinal control at high short period frequency <u>and</u> damping ratios, but not at low values of short period frequency <u>and</u> damping ratios.

3) Normal elevator control is preferred to DLC unless the parameter

$$\left.\frac{n_z}{\alpha}\right]_{ss} = \frac{V}{g}\frac{L_\alpha}{V_o} \text{ is low.}$$

4) The flying qualities of an airplane with a low $\left.\frac{n_z}{\alpha}\right]_{ss}$ and high short period frequency <u>and</u> damping ratio can be improved if lift control is combined with normal elevator control.

5) The flying qualities did not improve with combination control at low $\left.\frac{n_z}{\alpha}\right]_{ss}$ and low short period frequency <u>and</u> damping ratio. Further flight tests are recommended to substantiate this result.

6) The separate effects of short period frequency and damping ratio on the flying qualities when DLC or combination control is used is not known.

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6. Seckel, E., Miller, G. E., and Nixon, W. B., "Lateral-Directional Flying Qualities for Power Approach," Princeton University Department of Aerospace and Mechanical Sciences Report No. 727, June 1965.

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APPENDIX

Evaluation Flight Test Results/Comments

Conf.	Cooper Rating	Good Short Period Dynamics
1E $\frac{L_\alpha}{V_o} = 1.9$	2.0	Good flying aircraft. Tracks well. Attitude response good.
1F	3.0	Not bad. Sufficient acceleration for 30-35° bank angles. Pitch response satisfactory though somewhat slow. Tracks OK.
1K	2.0	Can definitely feel more acceleration response yet can't see much improvement in performance over that of pure elevator.
2E $\frac{L_\alpha}{V_o} = .75$	3.5	Requires large pitch change to pull g's in pull up or during transient entry into turn. Steady track OK, but pipper very sluggish when moving off target.
2F	3.0	Pitch response satisfactory though would like a little more. Less pitch change is required to pull g's in pull up or turn entry. Tracks better than previous configuration.
2K	2.5	Less attitude change required to pull g's than pure elevator case. Tracks well. Acceleration response is good. Can maneuver almost as well as basic Navion.
2K' $\frac{1}{2} M_{\delta_s}$ optimum	3.0	Attitude response not as good as 2K. Slightly harder to track.

Conf.	Cooper Rating	Bad Short Period Dynamics
3E $\frac{L_\alpha}{V_o} = 1.9$	5.0	Hard to stabilize and trim. Transient attitude very easily overcontrolled. Pitch response slow to come up to final value. Difficult to anticipate desired stick input. Can track a target if it cooperates with mild maneuvers. Not too bad once in steady turn. Acceleration OK in steady turn.
3F	6.0	Very difficult to stop pitch oscillations with stick. Once steady turn established, fair in tracking. Generally same as previous configuration except not enough attitude control.
3K	5.0	Acceleration response better, might be slightly better flying aircraft than pure elevator but difference hardly detectable.
4E $\frac{L_\alpha}{V_o} = .75$	5.5	Hard to stabilize and trim. Requires large attitude change to enter turn or pull up. Short period oscillation in pitch easily excited when maneuvering, tracking sloppy. Pitch response to stick input slow. Difficult to estimate magnitude and easily overcontrolled. Airspeed more difficult to control.
4F	6.5	Almost unacceptable because of poor pitch response to stick input. Very difficult to dampen out oscillations. Tracking possible if inputs are slow and smooth. Very difficult to pull lead on target. Response to normal stick inputs very oscillatory.

Conf.	Cooper Rating	Bad Short Period Dynamics
4K	6.0	No improvement over pure elevator case. Flaps appear to disturb short period a little more unless inputs are very smooth. Easy to overcontrol and cause pitch oscillations. Configuration has more attitude control than pure flap case.
4K'	6.5	Not as much attitude response as previous case. Short period oscillation harder to to dampen out.

$\frac{1}{2}$ M_{δ_s} optimum

TABLE I

CONFIGURATIONS

No.	L_α / V_o	ω_{sp}	ζ_{sp}	ω_{ph}	ζ_{ph}	$M_{\dot{\alpha}}$	$M_{\dot{\theta}}$
1	1.9	3.3	.615	.22	.12	-8.0	-1.5
2	.75	3.3	.615	.22	.15	-8.9	-2.6
3	1.9	1.2	.3	.4	-.08	-5.0	+1.90
4	.75	1.2	.3	.28	-.03	-1.9	+.66

TABLE II

AIRPLANE SPECIFICATIONS, FLIGHT CONDITION, AND DERIVATIVES

Gross Weight = W = 2750 lb.

Wing Span = b = 33.4 ft.

Mean Aerodynamic Chord = $\bar{c}$ = 5.7 ft.

Wing Area = S = 184 sq. ft.

h_o = 5000 ft.

$V_{trim} = V_o$ = 95 knots = 105 MPH = 158.5 ft./sec.

$q = \frac{1}{2} \rho V^2 = 25.6$ psf

$C_L = .59$

$C_D = 0.055$

$k_y^2 = 38.8$ ft.^{2}

$$D_v \equiv \frac{1}{m} \frac{\partial D}{\partial V} = 0.046 \text{ sec.}^{-1}$$

$$D_\alpha \equiv \frac{1}{m} \frac{\partial D}{\partial \alpha} = 23.2 \text{ ft./sec.}^2$$

$$T_v \doteq -\frac{g}{V} \frac{T}{W} = -0.023 \text{ sec.}^{-1}$$

$$\frac{L_\alpha}{V_o} \equiv \frac{1}{mV_o} \frac{\partial L}{\partial \alpha} = 1.9 \text{ sec.}^{-1}$$

$$\frac{L_v}{V_o} \equiv \frac{1}{mV_o} \frac{\partial L}{\partial V} = 0.002 \text{ ft.}^{1}$$

$$\frac{L_{\delta_f}}{V_o} \equiv \frac{1}{mV_o} \frac{\partial L}{\partial \delta_f} = 0.4 \text{ sec.}^{-1}$$

$$M_\alpha \equiv \frac{1}{I_y} \frac{\partial M}{\partial \alpha} = -8.0 \text{ sec.}^{-2}$$

$$M_{\dot\alpha} \equiv \frac{1}{I_y} \frac{\partial M}{\partial \dot\alpha} = -0.63 \text{ sec.}^{-1}$$

$$M_{\dot\theta} \equiv \frac{1}{I_y} \frac{\partial M}{\partial \dot\theta} = -1.50 \text{ sec.}^{-1}$$

$$M_v \equiv \frac{1}{I_y} \frac{\partial M}{\partial V} = 0$$

$$M_{\delta_e} \equiv \frac{1}{I_y} \frac{\partial M}{\partial \delta_e} = -11.0 \text{ sec.}^{-2}$$

$$M_{\delta_f} \equiv \frac{1}{I_y} \frac{\partial M}{\partial \delta_f} = -1.2 \text{ sec.}^{-2}$$

TABLE III

Cooper Pilot Opinion Rating System

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only*	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition*	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
		10	Motions possible violent enough to prevent pilot escape	No	No

*Failure of a stability augmenter.

TABLE IV

TABULATED RESULTS

No.	M_δ rad/ sec²/ in	L_δ rad/ sec/ in	K o/ o	$\frac{\alpha}{\delta}_{ss}$ rad/ in	$\frac{n_z}{\delta}_{ss}$ Δg/ in	$\frac{n_z}{\alpha}_{ss}$ Δg/ rad
1E	.41	-	-	.0375	.35	9.3
1F	-	.057		-.008	.206	-20.6
1K	.41	.027	-1.8	.034	.447	13.3
2E	.48	-		.042	.162	3.7
2F	-	.0435		-.0104	.190	-16.7
2K	.48	.033	-1.9	.036	.295	8.3
2K'	.24	.039	-4.4	.0129	.235	18.7
3E	.155	-		.108	1.0	9.3
3F	-	.0435		.057	.75	12.3
3K	.155	.033	-5.8	.153	1.57	10.3
4E	.22	-		.153	.565	3.7
4F	-	.0495		.065	.32	13.9
4K	.22	.021	-2.6	.15	.69	4.25
4K'	.11	.032	-8.0	.097	.475	5.25

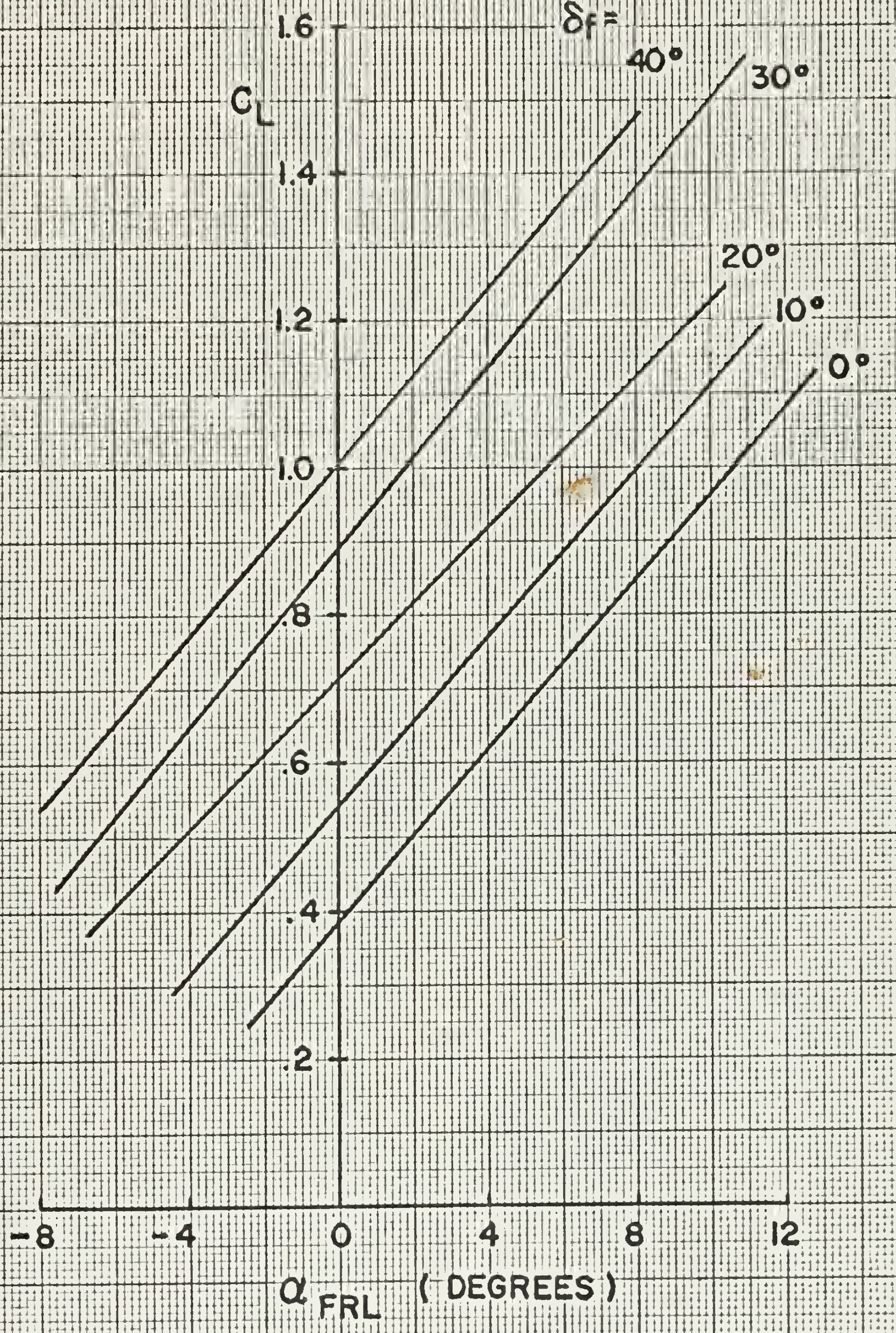

Figure 1. Lift Coefficient Versus Angle of Attack for Various Flap Deflections. Flight Test of Similar Navion. Reference 4

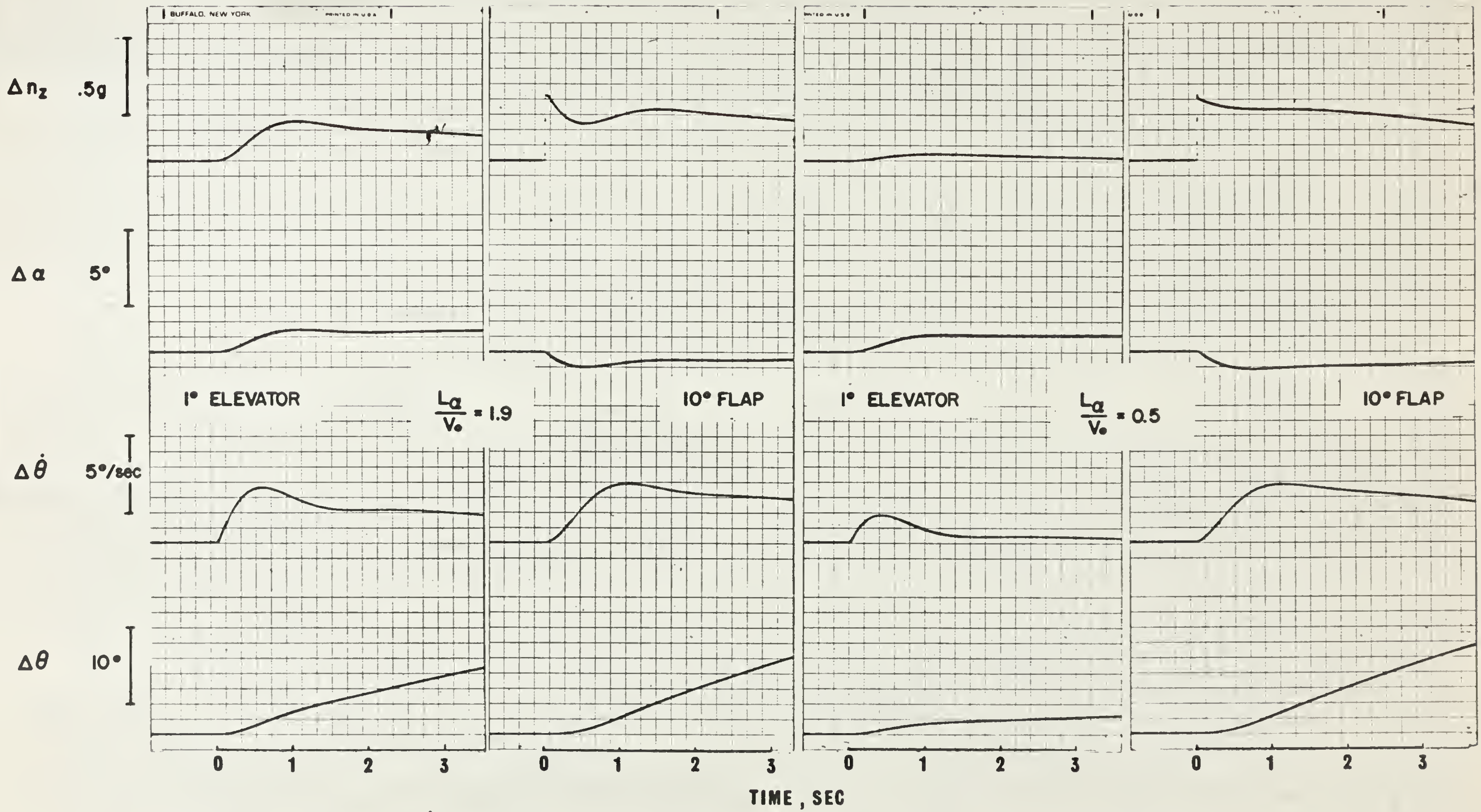

Figure 2 Comparison of Responses to Step Elevator and Flaps at Two Values of L_α / V_o

$\omega_{sp} = 3.3 \quad \zeta_{sp} = .615$

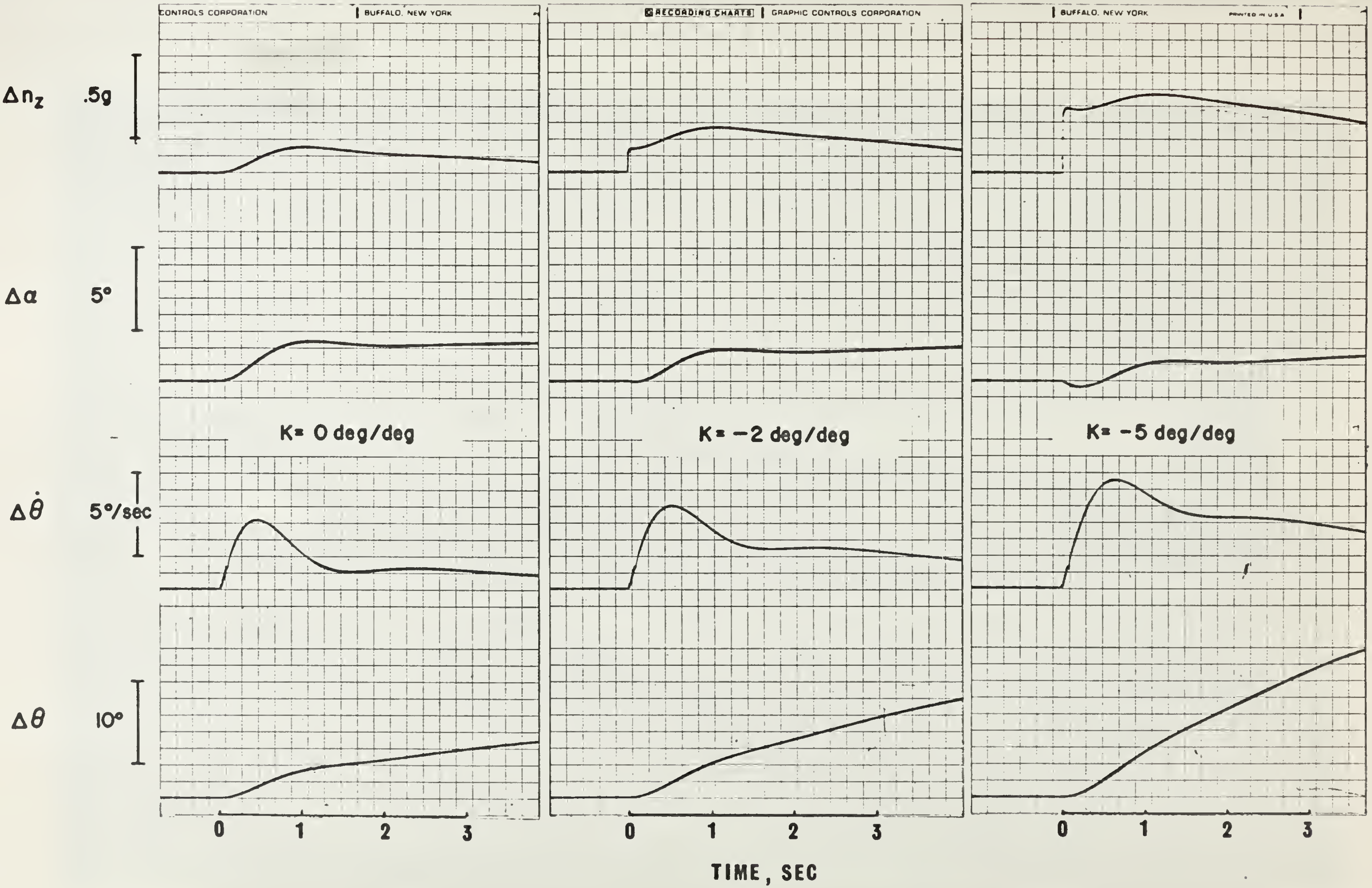

Figure 3 Comparison of Responses to Step Stick Inputs at Three Values of Flap to Elevator Gearing Ratio, K

Figure 4 Princeton Variable Stability Navion

Figure 5 Cockpit Arrangement

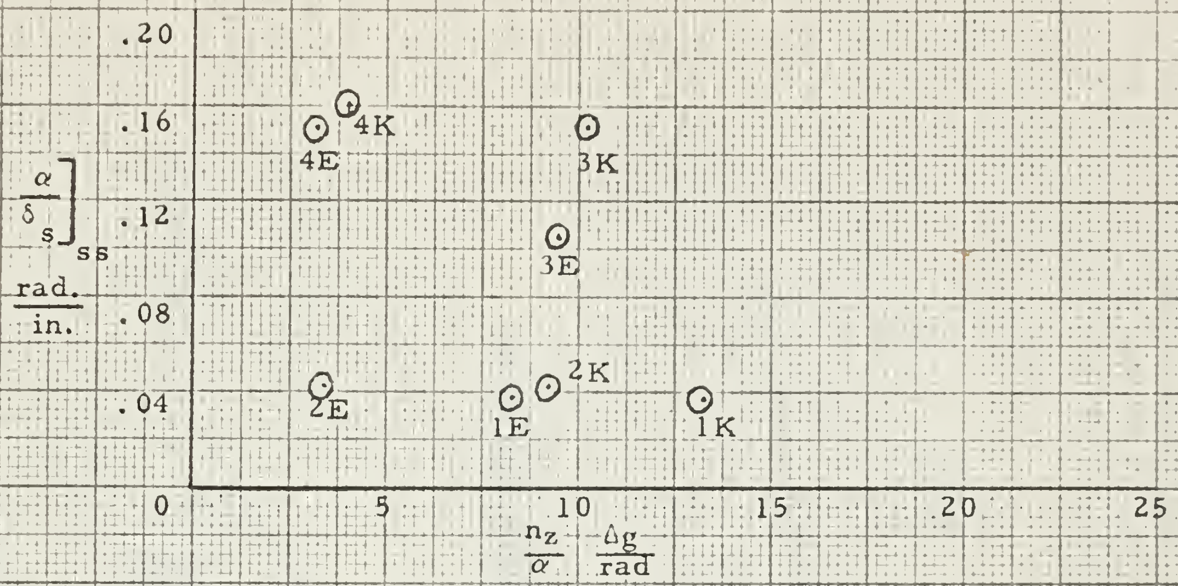

Figure 6a. Longitudinal Steady State Angle of Attack Gains Selected for Elevator and Combination Controls

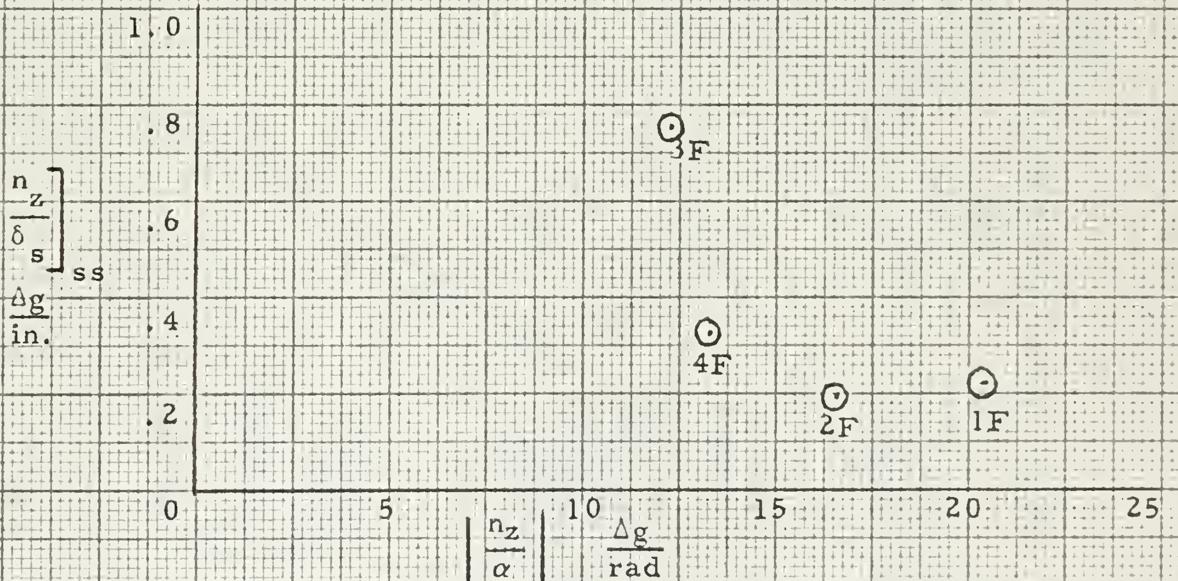

Figure 6b. Longitudinal Steady State Normal Acceleration Gains Selected for Flap Control

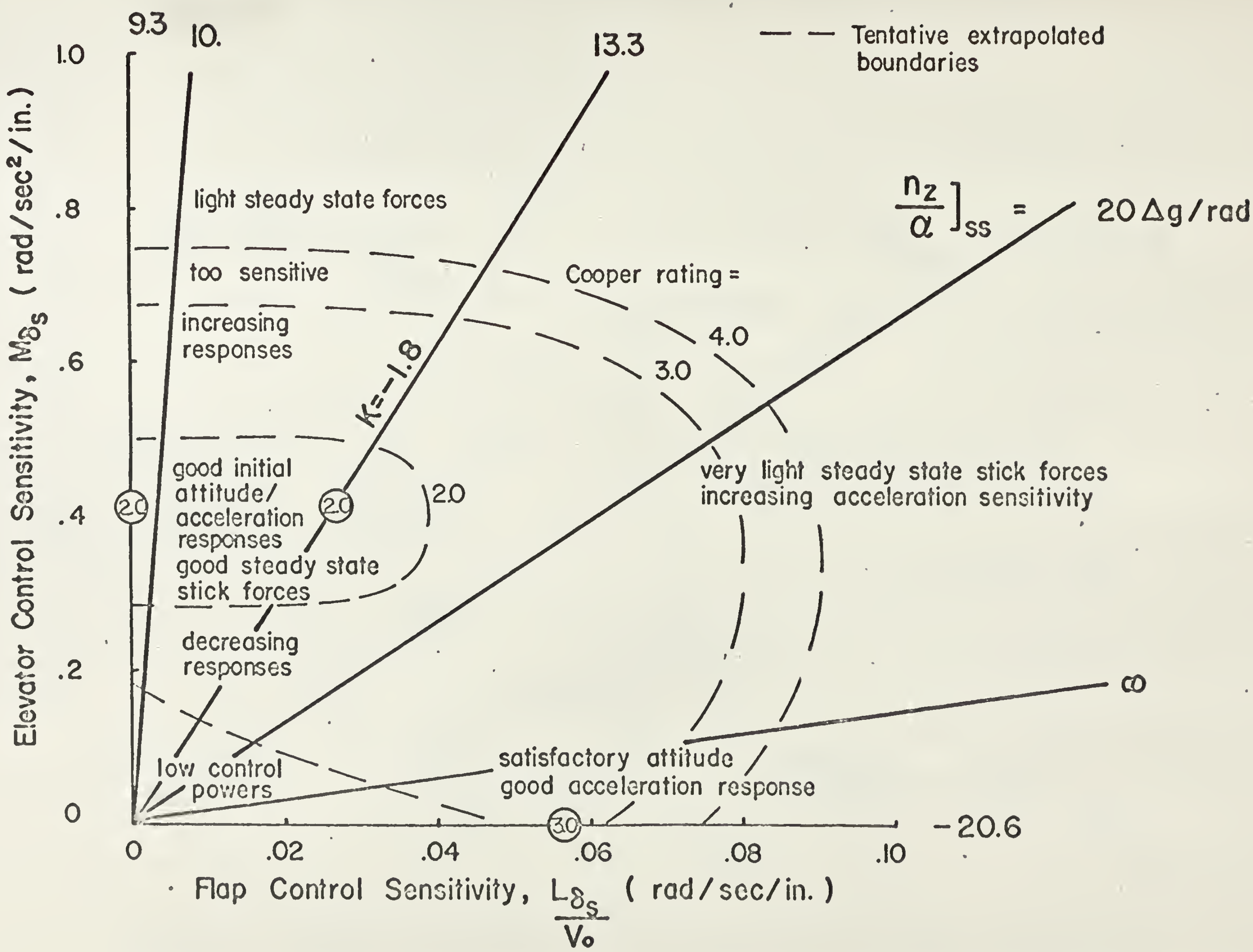

Figure 7a. Tentative Longitudinal Control Boundaries with Selected Optimum Sensitivities

Configuration 1., $L_\alpha / V_o = 1.9$ $\omega_{sp} = 3.3$ $\zeta_{sp} = .615$

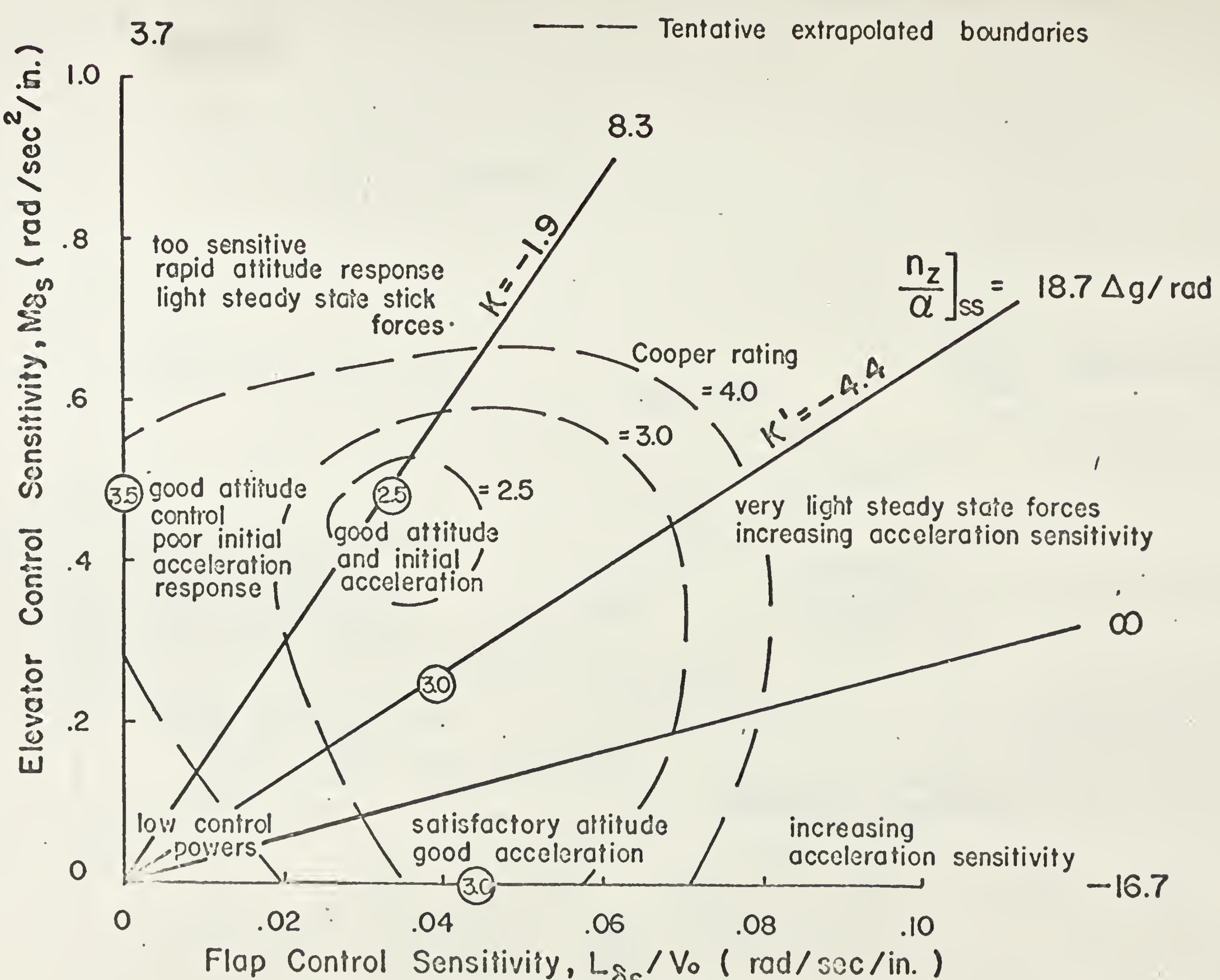

Figure 7b. Tentative Longitudinal Control Boundaries with Selected Optimum Sensitivities

Configuration 2., $L_\alpha / V_o = .75$ $\omega_{sp} = 3.3$ $\zeta_{sp} = .615$

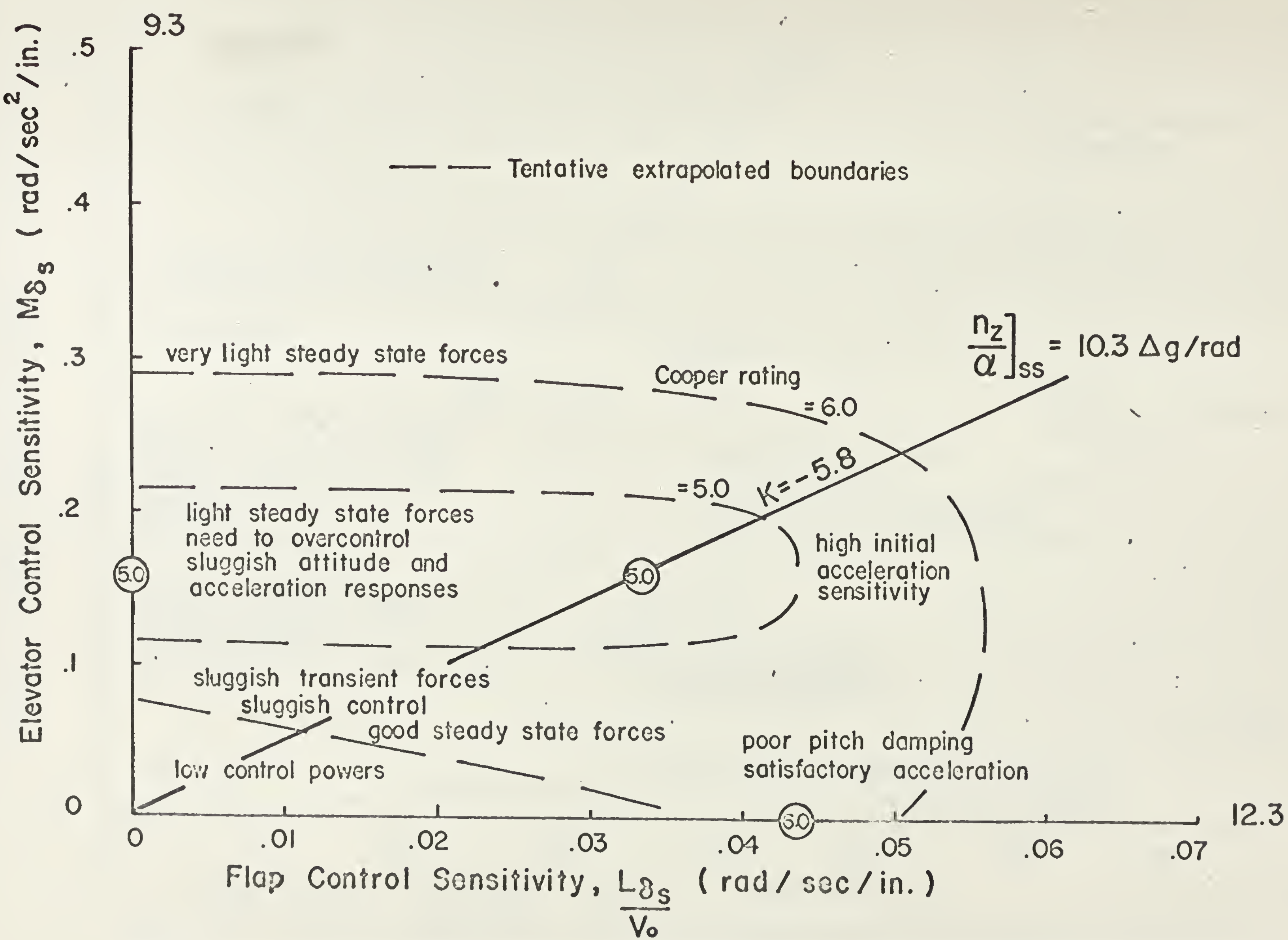

Figure 7c. Tentative Longitudinal Control Boundaries with Selected Optimum Sensitivities

Configuration 3., $L_\alpha / V_o = 1.9$ $\omega_{sp} = 1.2$ $\zeta_{sp} = .3$

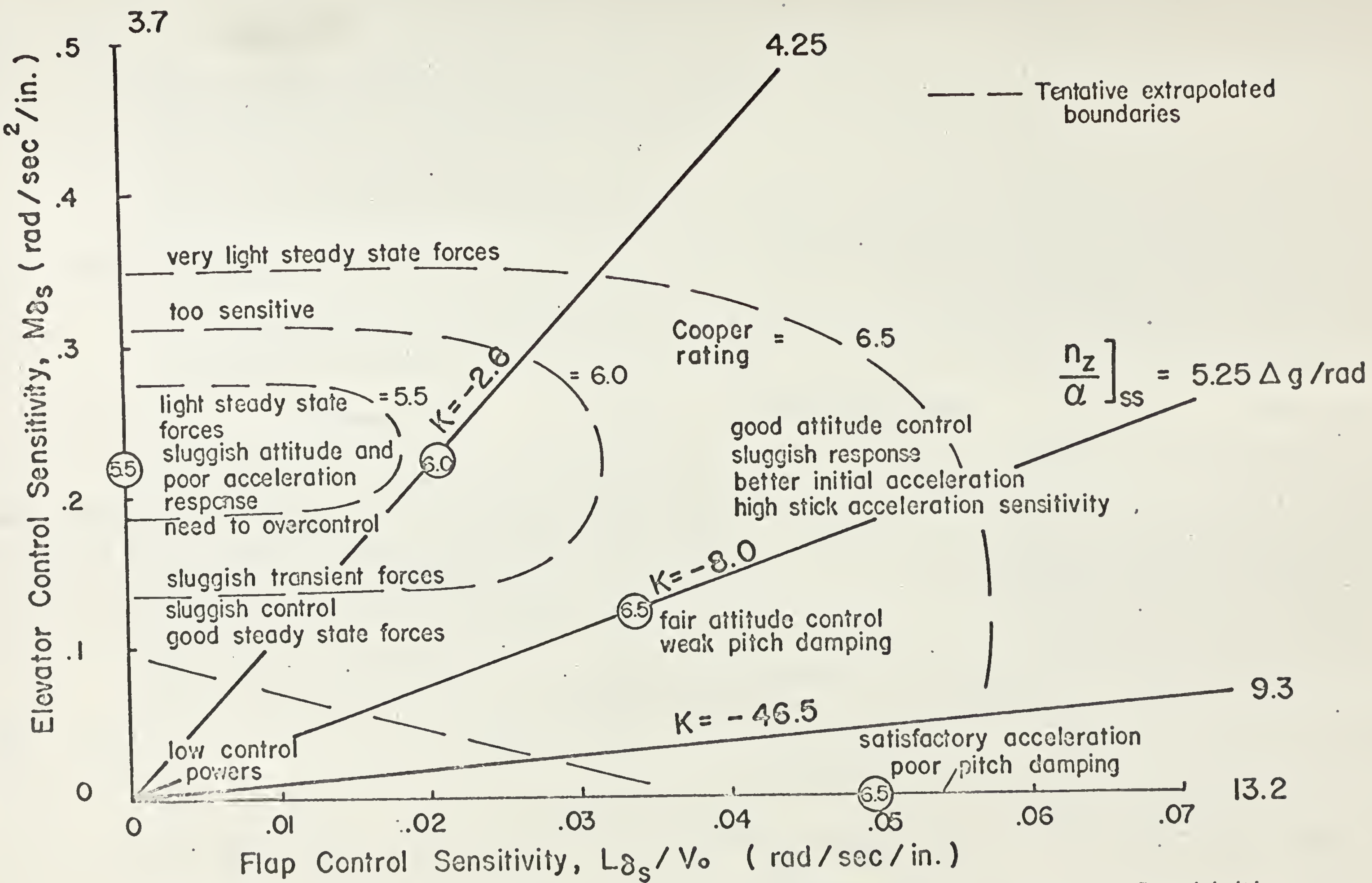

Figure 7d. Tentative Longitudinal Control Boundaries with Selected Optimum Sensitivities

Configuration 4., $L_\alpha / V_o = .75$ $\omega_{sp} = 1.2$ $\zeta_{sp} = .3$

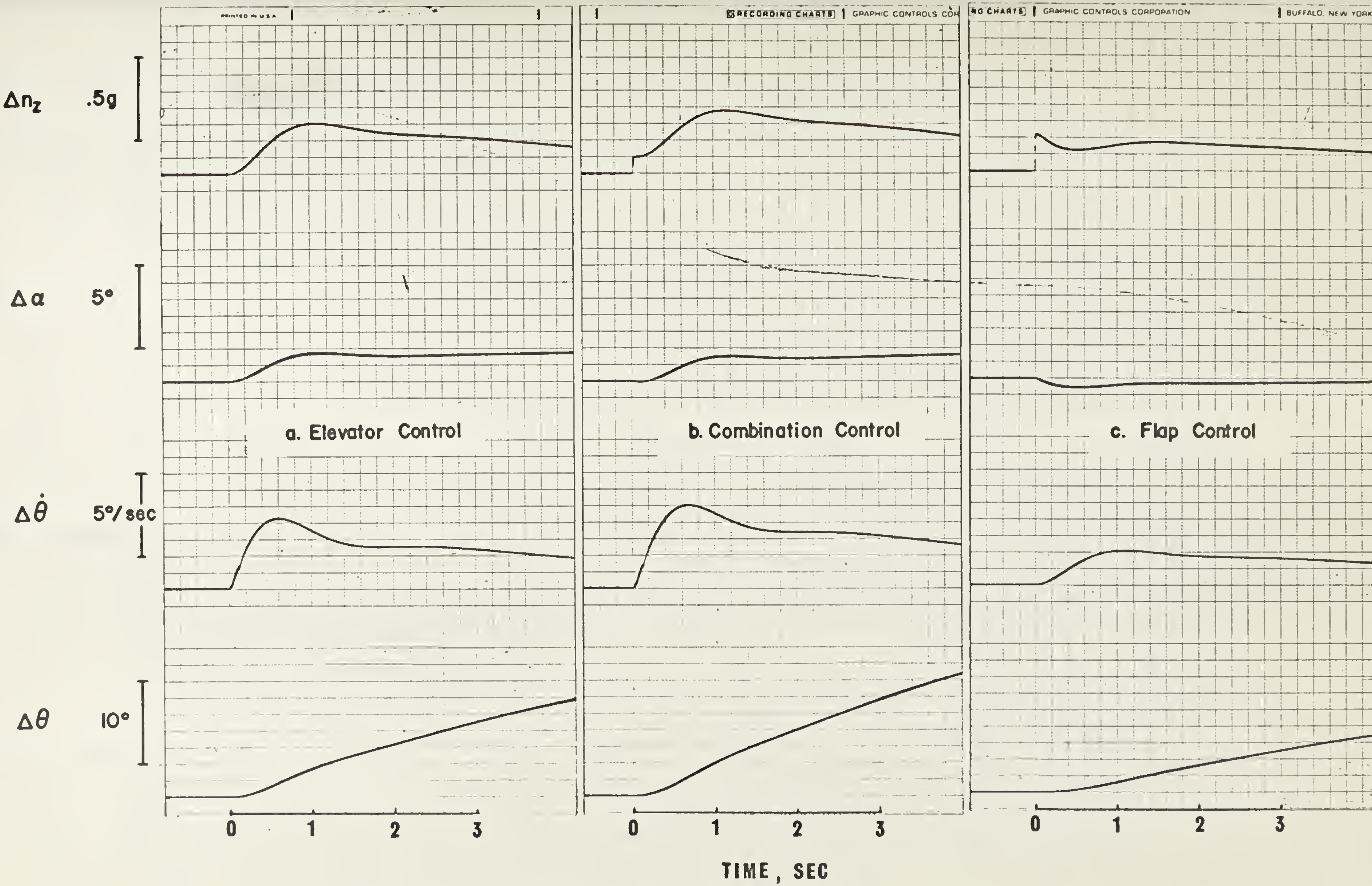

Figure 8 Comparison of Three Methods of Control
Analog Computer Responses to Unit Stick Step Input at Selected Sensitivities
Configuration 1 $L_\alpha / V_o = 1.9$ $\omega_{sp} = 3.3$ $\zeta_{sp} = .615$

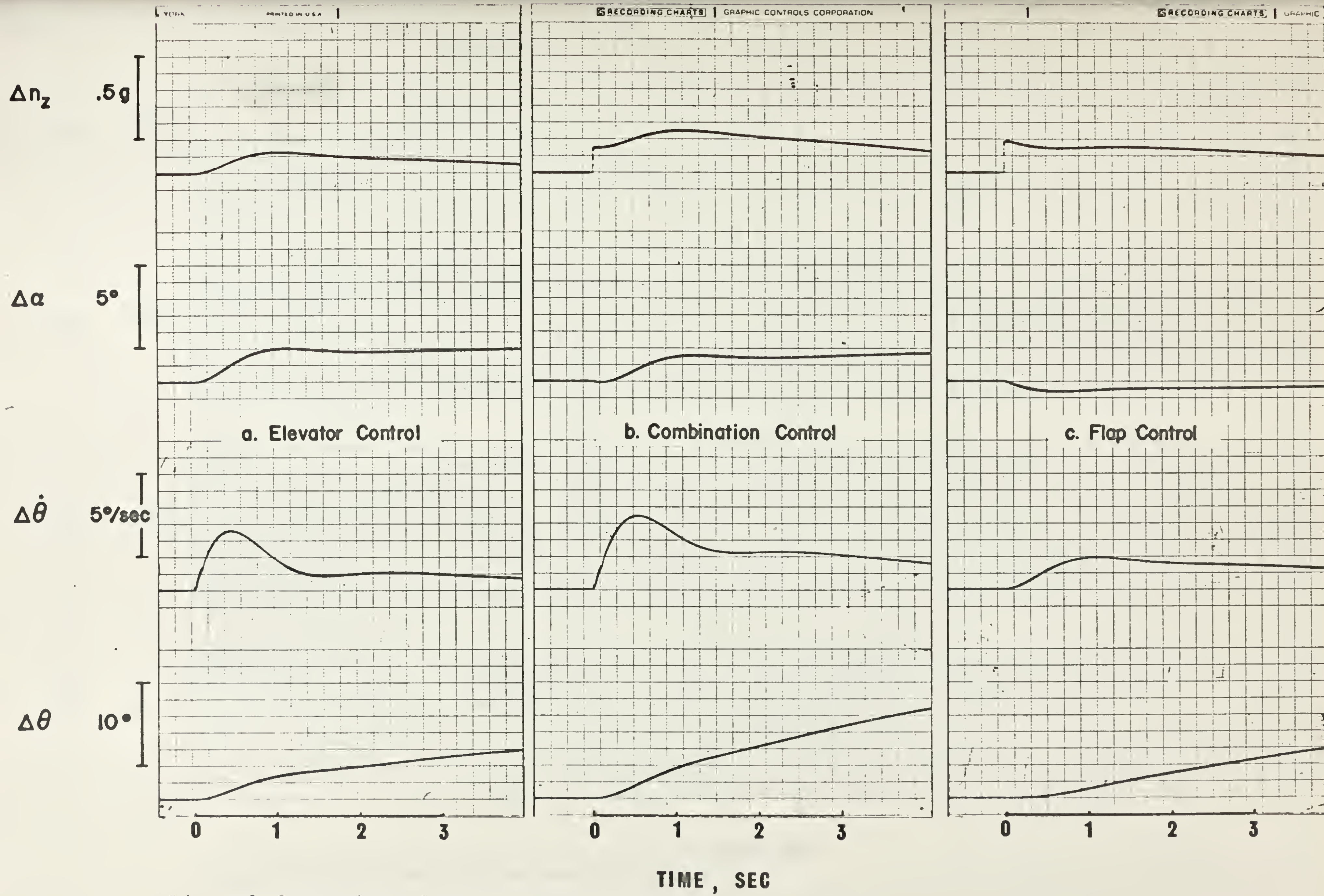

Figure 9 Comparison of Three Methods of Control
Analog Computer Responses to Unit Stick Step Input at Selected Sensitivities
Configuration 2 $L_\alpha/V_o = .75$ $\omega_{sp} = 3.3$ $\zeta_{sp} = .615$

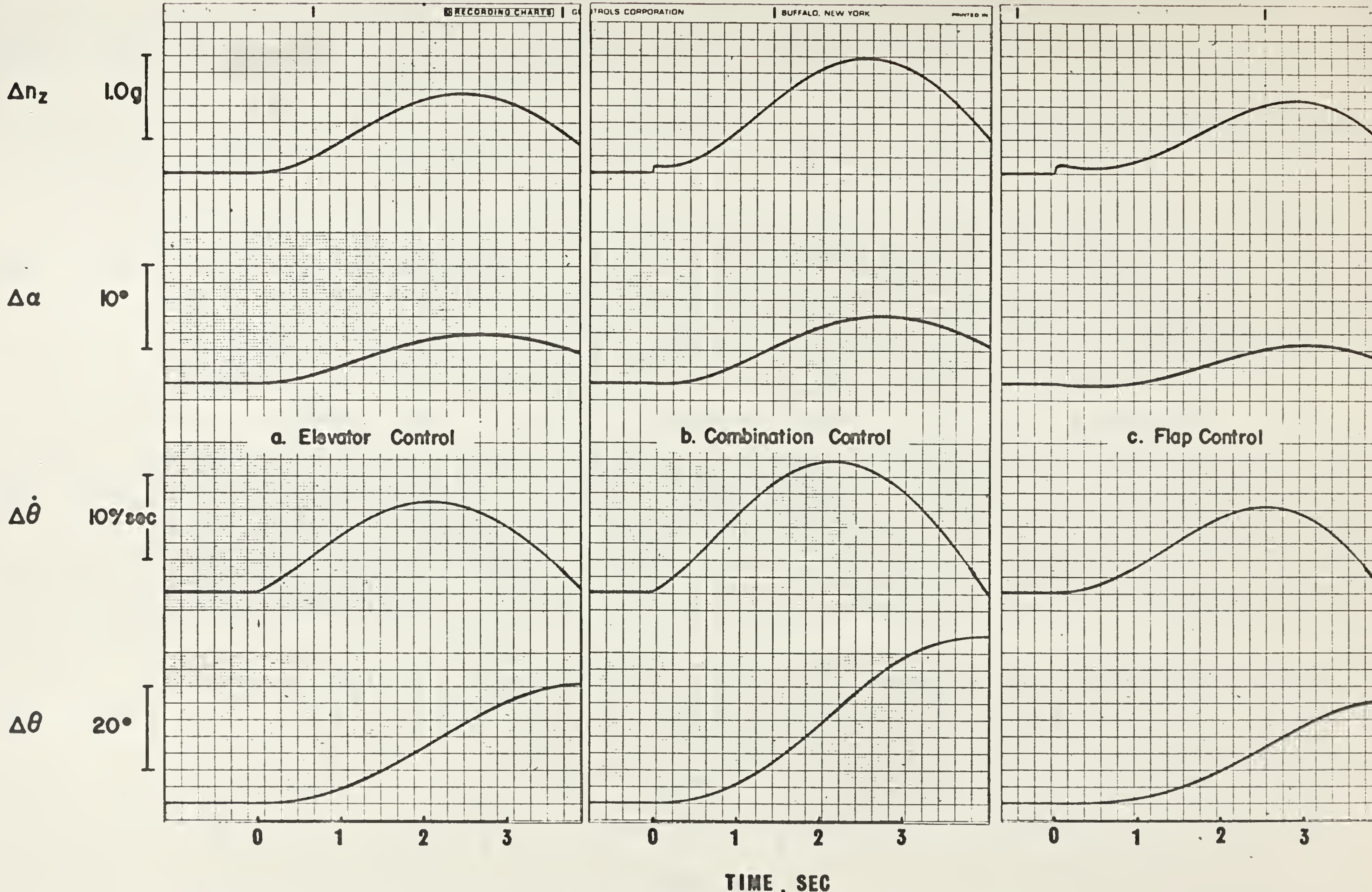

Figure 10 Comparison of Three Methods of Control
Analog Computer Responses to Unit Stick Step Input at Selected Sensitivities
Configuration 3 $L_\alpha / V_o = 1.9$ $\omega_{sp} = 1.2$ $\zeta_{sp} = .3$

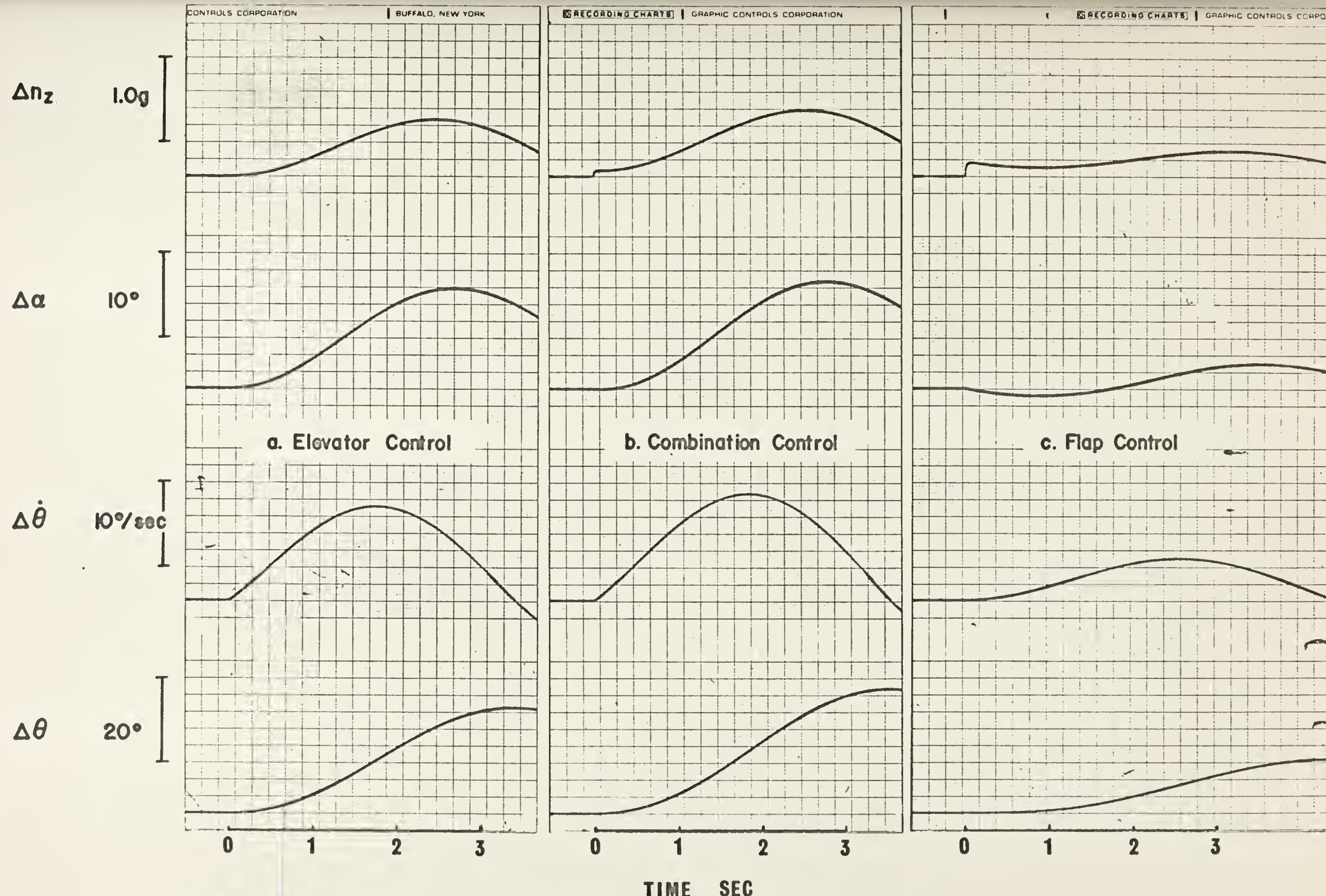

Figure 11 Comparison of Three Methods of Control
Analog Computer Responses to Unit Stick Step Input at Selected Sensitivities
Configuration 4 $L_\alpha / V_o = .75$ $\omega_{sp} = 1.2$ $\zeta_{sp} = .3$